J. BJERKNES AND H. SOLBERG ON METEOROLOGICAL CONDITIONS FOR THE FORMATION OF RAIN.[1]

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Force of circumstances during the Great War compelled Norwegian meteorologists to depart from the beaten path in weather forecasting and to adapt themselves to the use of such simple elemental data as could be obtained easily without expensive instrumental equipment and trained meteorological observers. On the basis of numerous wind observations, lines of flow were drawn, and largely from this simple beginning grew a series of studies of atmospheric movements that have yielded results of much importance to students of the forecast problem.

The authors have classified all rain occurring in Norway according to the mode of its formation and have illustrated the various types by charts and descriptive text. They fully recognize that the predominating influence in the formation of rain is the ascent and cooling of the air, hence their first inquiry concerns the conditions which develop and sustain ascending motions.

A comparison between the results obtained in Norway with the experience of forecasters in the United States is difficult by reason of the geographical position of the former and its exposure to the Atlantic Ocean on the west in the direct path of cyclonic storms which move in from the vicinity of Iceland.

That part of North America which corresponds in latitude to Norway extends from about Juneau, Alaska, northward to Point Barrow, the most northerly point of Alaska. Only a narrow strip of the coast in the latitude of Juneau (58° 18′) has any physical resemblance to the Norwegian coast. The meteorology of the coastal strip is fairly well known and in many particulars bears some resemblance to that of the southern Norwegian coast, but owing to the decided difference in the direction of the trend of the coast of Alaska as compared with Norway, the meteorological conditions which obtain over the greater part of the two regions are not similar.

Orographic rain.—The mountains of Norway trend almost parallel with the direction of the coast line, whence it follows that oceanic winds must ascend as they pass inland; consequently the regions of greatest rainfall are on the western slopes facing the ocean. The height of the mountains is not great and indeed there does not seem to be any very direct relation between altitude and depth of precipitation.

Cyclones passing inland over Norway are, of course, associated with northwest winds in their rear. As these winds cross the coast line they become ascending winds, whence it must appear that a large proportion of the precipitation of Norway might also be classed as cyclonic rain, although the authors do not so class it. Familiarity with the detailed topography of the coast line and the hinterland enables them to point out relations which to one not so familiar with the surface relief of the country would find difficulty in explaining. It is pointed out that in the cases under discussion the heaviest rain occurred along a narrow strip about 30 kilometers back from the coast. This condition is the normal one in Norway, there being, however, more rain in the south than in the north.

The authors distinguish between pure orographic rain and rain that is deposited by a westerly current, which bears rain even over the sea entirely independent of orographic influences. They say, speaking of orographic rain in western Norway:

> Pure orographic rain in western Norway seldom exceeds 5 mm. in 24 hours even in the zone of maximum amounts. A westerly current containing showers over the sea may, however, in the same zone cause rain up to 30 mm. in 24 hours.

This is explained as follows: Shower-bearing winds are retarded as they pass inland and move with smaller velocity or even stop. The amount of precipitation from each shower will, of course, be greater the slower the movement, and thus the showers may add to the orographic precipitation more than they can give alone over the sea, provided that they have not meanwhile diminished in intensity. The region of maximum amounts of precipitation is a place where showers for topographical reasons are forced to move slowly without a decrease in intensity.

Stable and unstable air currents will behave differently when they cross a mountain range. Air masses of a stable current being forced to ascend against the mountain will become colder and thus heavier than the surrounding air at the same level and will resist further vertical displacement. The air in unstable currents, on the other hand, will become lighter than the surrounding air as it ascends, and thus supplements the initial motion. Therefore stable air currents are more likely to pass around the mountain than to override it, and the amount of orographic rain will, of course, be greater in the latter than in the former.

Unstable currents, it is stated, are those which originate in cold regions and are later warmed on the underside. In all seasons northerly currents are most likely to become unstable since they bring air from colder to warmer parts of the earth. Unstable currents may, however, come from any direction, even the south; but they are the branches of originally cold currents following curved paths.

Air currents originating in warmer parts of the earth will be cooled from below as they reach colder regions and will therefore be stable. In such currents, however, the cooling of the lower layers by the ground may lead to the formation of fog, or even a slight drizzle.

Summarizing their studies as to orographic rains the authors conclude:

> Pure orographic rain, which necessarily forms as well in stable as in unstable currents, occurs only in connection with mountains at least 1,000 meters high. Showers due to instability may, in particular cases, add considerable amounts to that of the pure orographical rain and make even orographical rain possible in connection with smaller obstacles. The effects of orographical rain are strongly restricted by the tendency of all stable air currents to curve round the mountains horizontally.

The authors recognize the fact that the greater part of orographical rain will occur simultaneously with rainfall of other origin. The combined cyclonic and orographical rain is much more abundant than the simple orographical rain of homogeneous currents.

The conditions which give rise to ascending currents in the free air are discussed at much length and in great detail for which the reader must consult the original

[1] *Geofysiske Publikationer*, Vol. II, No. 3, Kristiania, 1921.

contribution. Three different types are distinguished as shown in figure 1 below.

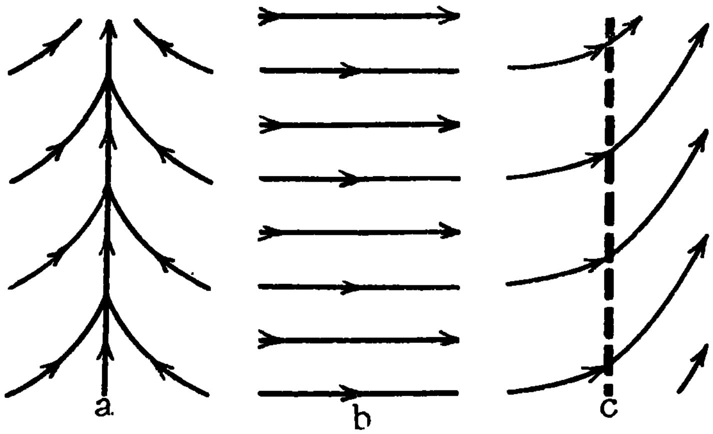

FIG. 1.—[Original No. 5]; *a*. Field of flow in a stationary line of convergence; *b*. Additional field of translation; *c*. Resulting field of flow in a moving line of convergence.

It is the experience of Norwegian meteorologists that the regions of strong convergence of the winds are arranged along narrow strips, or lanes corresponding to lines of convergence in the field of horizontal motion. The simplest form of a line of convergence is that shown in figure 1a. In this case lines of flow pass symmetrically from both sides toward a central line of flow. This type, it is remarked, is a rather special one and does not often occur in nature. A more general line of convergence is obtained when a vector field of constant translation (Fig. 1b) is added to the field of a symmetrical line of convergence (Fig. 1a) which results in a field of flow of the type represented by figure 1c. The former line of convergence is represented by the dotted line, which is no longer a line of flow but rather a line through the places having wind-shift at the moment to which the map in question refers. Thus it corresponds to a more or less accentuated trough-line in the field of pressure.

The new shape of the wind field implies, however, no change in the field of vertical motion. This field being constructed by aid of the equation of continuity will be just the same for figure 1a and figure 1c in both cases showing a narrow belt of rapidly ascending motion along the line of convergence, figure 1a and figure 1c, respectively. The ascending motion at the wind-shift line is much greater than that occurring in simple homogeneous currents without discontinuous changes of wind direction and velocity. Clayton [2] has pointed out the fact that a system of converging winds is indicative of precipitation but the application of the idea to forecasts of rainfall in the United States has not made much progress for various reasons, chiefly because lines of convergent flow are not clearly shown by reason of the distance between reporting stations.

The authors now consider cases of warm air displaced by a moving wedge of cold air, cold-front rain, and the conditions under which a moving wedge of cold air may produce orographical rain in connection with the topographic features of Norway.

The cold air may advance from the west in the rear of a V-shaped depression and also in many other types of pressure distribution.

[2] Clayton, H. Helm, Relation between rainfall and synoptic winds; MO. WEATHER REV. 44: 80-81.

Another condition under which air is made to ascend is that of a warm front advancing against a retreating wedge of cold air, such as would be involved in the advance of a cyclone into regions occupied by a retreating anticyclone. The thought here is centered upon the warm front of the cyclone as it advances into regions of colder air. The authors' conception of the phenomenon is illustrated in Figure 2 below.

In this figure the line of discontinuity is drawn through the cyclone without the deformation produced by the mountains of Norway, and the figure thus represents an idealized cyclone over perfectly flat ground. The shaded area indicates the region of precipitation at the moment of observation. It consists of the warm-front rain extending as a broad, curved zone in front of the tongue of warm air, and the much narrower band of cold-front rain in the rear. The upper part of Figure 2 represents a vertical section through the cyclone to the north of the center. The succession of the weather, reading from right to left, is also shown. Such a section cuts the rain area only once, corresponding, thus, to a single rainfall of duration according to the relative distance from the center.

The lower part of Figure 2 is a vertical section sketched through the cyclone to the south of the center. It gives, from right to left, the succession of weather to the south of the passing cyclone. First is the passage of typical warm-front rain preceded by an extensive shield of Ci., Ci-St., and A-St. clouds, then a rain-free, relatively warm, spell of weather during which the cloud shield of alto-cumulus appears, announcing the approaching cold-front rain.

With regard to the height above the surface that the bounding surface of a cyclone may reach the authors place it at about 9 km., as shown in the lower part of figure 2. In explanation they say:

All the clouds preceding the warm-front rain, cirro-stratus, alto-stratus, and mammato-stratus, are typical sheet clouds, and their mutual connection makes it probable that they belong to the same inclining boundary surface which can be observed in the lower atmosphere. Even the tufted cirrus is a sign for the existence of a surface of discontinuity at that height. The tufted cirrus must consist of ice crystals falling from the tufts through a well-defined surface of discontinuity into a layer with different velocity from that of the tufts.

The ice crystals will there form a long tail in the direction of the vectorial difference of winds above and below the surface of discontinuity.

As tufted cirrus always move nearly in their own longitudinal direction, the tufts being directed forward, it may be concluded that the velocity up above the surface of discontinuity has stronger component forward than the velocity below. We thus get a picture of a strong upper current penetrating forward and probably a little upward in front of the continuous cyclonic cloud masses. It is not improbable that we here observe the uppermost part of the warm current above the warm-front surface. * * *. These questions, however, must be more closely examined before definite opinions can be stated.

The conditions favorable to the development of local showers are discussed with particular reference to the topographic control exerted by the mountains of Norway. Typical summer rains are said to develop first in the mountains lying within reach of the sea breeze of the first several days. It should be said that the sea breeze penetrates inland a certain distance on the first day and retires toward the coast at night; the second day it has some of the sea air in front of it which was brought in the first day and forces this air to ascend. Conditions are therefore more favorable to the development of local showers the second day than the first and still more favorable on the third, and so on. As the velocity of the sea breeze is small the regions farthest from the coast will be reached after several days. But if the calm-weather type persists the whole country will, sooner or later, be covered by air which has been previously over the sea. When that stage is reached the great moisture content permits local showers to develop over the whole country wherever strong convective currents are rising. This is the type of continental summer rains and it may persist for weeks at a time.

Numerous charts are presented illustrating the development of showery weather in summer and the gradual change from showers to fair weather; these, however, apply in particular to the conditions which obtain in Norway. The following conclusion is of considerable interest to forecasters in the United States:

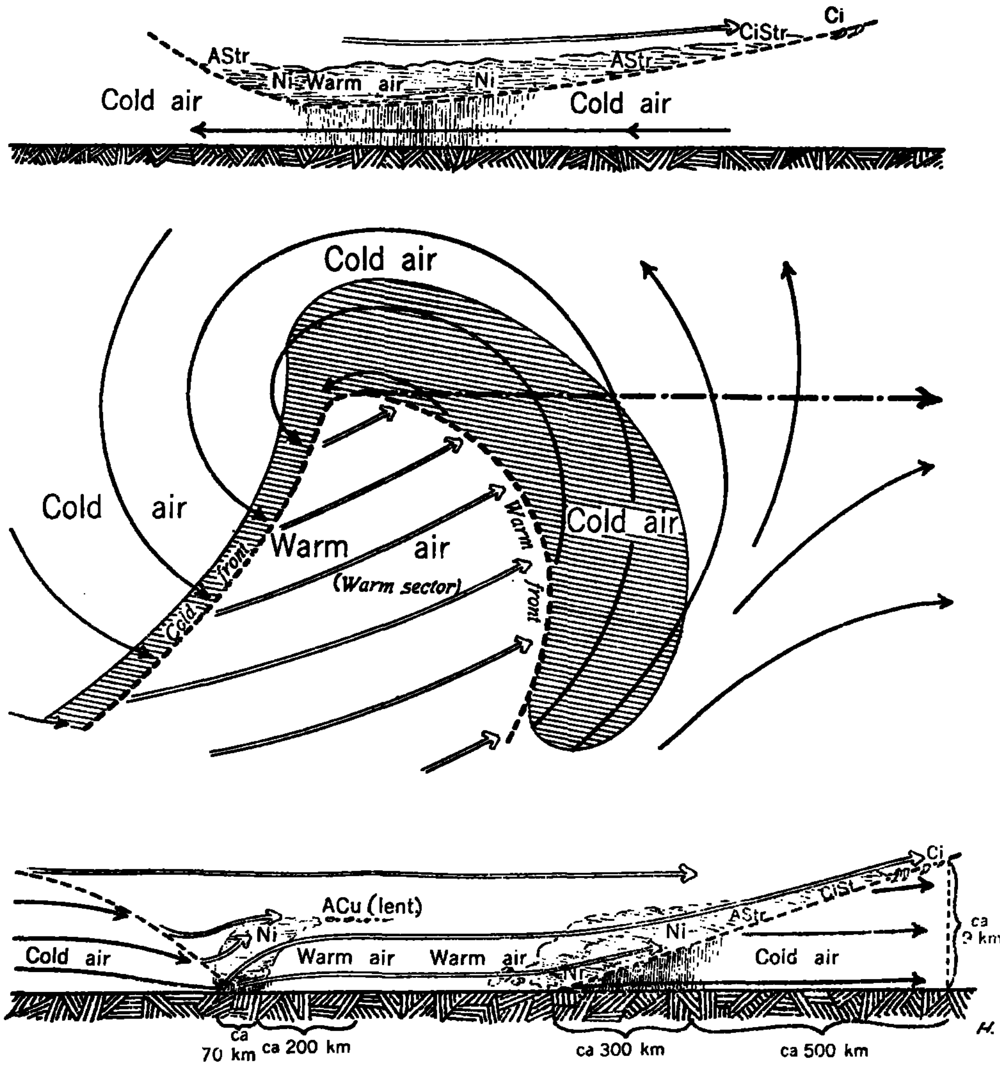

FIG. 2.—[Original No. 18.] Idealized cyclone.

> The properties of the air in respect to stability and content of moisture are more important factors for the occurrence of local showers than the general distribution of pressure.